Final Report for ONR Grant Entitled Tropical Cyclone Intensity Change: Simulation and Analysis

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A. Scientific Reporting on this Research

A.1 Long-Term Goals:

The long-term goals of this project are to understand various pathways to tropical cyclone intensity change and how robust these individual mechanisms of intensification are. That is, are there preferred and rare paths to tropical storm intensification? Further, to demonstrate the proposed intensification pathways through both observations and numerical modeling.

A.2 Scientific Objectives:

The primary goals of this project are to explore the potential for externally forced tropical cyclone intensification:

(i) To identify the physical mechanisms responsible for intensity change of tropical storm and hurricane systems and determine how robust these mechanisms are. For example, can a storm intensify if the atmospheric conditions are ideal, but the ocean surface is too cold? Which condition is most critical?

(ii) To utilize the best available numerical modeling technology to simulate these systems and thereby to further test hypotheses regarding the mechanisms of intensity change and to determine what minimum level of physical detail is required for a numerical model to correctly simulate tropical storm intensity change.

(iii) To relate the results from steps (i) and (ii) to information that can be determined from the numerical products currently available to the forecasters.

(iv) To provide quality data analyses to supplement existing synoptic climatologies of tropical cyclone intensification and utilize these case studies as models for the idealized model simulations.

Each of these goals has been met. The non-hydrostatic form of the Penn State/NCAR mesoscale model continues to be used to explore objectives (*i*) – (*iii*). Storms from the Tropical Cyclone Motion 1990 and 1993 (TCM-90, TCM-93) field experiments, as well as Atlantic hurricane data have been used to meet objectives *(i)*, *(iii)* and (*iv*).

A.3 Overall Progress of this Work:

The Penn State/NCAR non-hydrostatic mesoscale model (MM5) has been used to simulate idealized tropical cyclone-environment interactions successfully. To reach this stage, substantial model enhancements and additions were required. These are detailed in Section A.5 below. Early results have been reported to the community, with much positive feedback. Presently, further exciting results are being obtained and processed.

Through the course of this grant, the observational component of this research took four separate paths. These paths are briefly described here. The technical accomplishments required and results are given below.

Eight individual case studies of intensifying tropical cyclones have been compiled. The majority of these systems were interacting with troughs in their environment. He used potential vorticity diagnostics to characterize the storms and the other significant features in the storm environment. Such scalings are thought to be useful in choosing initial conditions for the idealized modeling study discussed above.

A satellite algorithm to survey the tropical environment has been developed. This system compiles information on the types of weather systems in the region. This automated satellite identification, tracking and classification system has proven to be a powerful research tool for characterizing the tropical atmosphere.

The links between tropical cyclone lifetime intensity and recurvature time have been explored for both the Pacific and Atlantic basins.

Detailed analyses of radiosonde data from TCM-90 have been used to study height and temperature variations of the tropopause in the presence of an approaching tropical cyclone.

Results from all of these components of our research have been presented and published in conferences around the country and beyond. A number of journal articles are already in print, with more being written to complete the dissemination of our recent findings.

A.4 Major Results and Findings:

(a) Idealized, non-hydrostatic simulations of tropical cyclone intensity change

Idealized, non-hydrostatic simulations of development of an isolated tropical cyclone demonstrate that the MM5 (Penn State/NCAR) model is capable of intensifying both relatively weak and strong vortices placed in a convectively favorable or neutral regime. This simulation of the quiescent vortex was used to evolve a nearly symmetric cyclonic vortex with a realistic anticyclonic outflow from an initially quasi-barotropic cyclonic vortex. This is the control simulation, and the model fields at 24 h provide the basis for other simulation cases.

The 24 h vortex was placed in various dynamic environments to investigate the relative roles of horizontal shear, vertical shear, sea surface temperature, and combined horizontal and vertical shear (representing a trough feature). The environmental fields were added as anomalies to the developed vortex fields, reinitialized, and then integrated forward in time. Analyses are stratified in terms of environmental and initial vortex characteristics. Environmental discriminators are shear, SST, potential vorticity, signature size of the trough (if one is present) or depth of the layer of shear (no trough). Vortex discriminators are size,

strength and intensity of the initial vortex, presence or absence of the outflow anticyclone, and distance from the trough (for the last set of cases).

The choice of the evolved (24 h) vortex as the initial storm state came after a series of simulations indicating that a purely barotropic initial vortex in a moist, baroclinic environment was highly susceptible to decay in a sheared environment. This is consistent with the studies by Jones of vortex motion in a dry, sheared flow. In her simulations the vortex continuously decays from the initial time. Since we are interested in simulations lasting days to study the complete sequence of events as the trough and storm approach, interact and release, this outcome (vortex decay) was not acceptable. The method of initializing the environment as a perturbation on the vortex-only fields enables us to superpose multiple components of the initial conditions without loss of information. The dynamic initialization following this superposition removes the majority of "sound" and gravity waves.

The various moderate shear regimes alter the vortex path to intensification, that is $p_{MIN}(t)$ differs among the cases. However, the ultimate intensity reached by these tropical cyclones seems largely the same.

Present indications are that a trough to the north of the storm is more favorable for intensification than other configurations of the storm-trough couplet. This is at variance with our initial expectation that a trough to the northwest of the tropical storm would provide an enhancement of the storm intensity. Troughs in this relative location (northwest of the TC center) weakly suppress development. Once again, once the trough proceeds further to the north or away from the tropical cyclone, the storm increases it intensification rate.

(b) Observational case studies of tropical cyclone intensification in the presence of a trough

Eight intensifying tropical cyclones were studied. Cases were chosen based on the presence of a rapid intensification period when a trough was moving through the domain. Both Atlantic (6) and western Pacific (2) cases were used. Systems were characterized according to their (i) size, (ii) horizontally-integrated potential vorticity (PV) over the area defined by the size; (iii) dynamic depth; (iv) vertically-integrated PV in the core of storm. A similar set of characteristics were developed for the trough, with the addition of (v) vertical wind shear. The storm-trough separation distance was also calculated.

Result from this study indicate greater storm intensification for storms that are relatively deep (when compared to the trough) and as the storm and trough approach. The shear associated with the trough also related weakly to storm intensity. These results are consistent with earlier studies and imply that a relatively large tropical storm can attain high intensities in the presence of a trough. These studies are not able to attribute causality.

(c) Automated identification and tracking of tropical weather systems using satellite data

An automated system for satellite data diagnostics of the tropical atmosphere was developed and tested. The purpose of this study was to assess the relative frequency of other organized tropical weather systems relative to tropical cyclones. This allowed for analysis of the tropical environment from cloud top temperature information, identifying the tropical cyclone and any other significant weather phenomena in the region. This perspective is important when trying to build a picture of the tropical atmosphere in which the cyclone is evolving.

(d) Observational links between lifetime maximum storm intensity and timing of recurvature

This research demonstrated the frequent coincidence between tropical cyclone recurvature and attainment of the storm's maximum lifetime intensity. The signals were especially clear for storms in the western North Pacific, with over 80% of storms reaching their peak intensity prior to recurvature. Inclusion of storms that later underwent extratropical transition in the North Atlantic database (not done in the western North Pacific data) may have contributed to the weaker signal in the Atlantic data. In both basins, weak storms were more likely to peak at recurvature time than were strong storms.

(e) Radiosonde analyses of tropopause variations near tropical cyclones in TCM-90

A "smart" spatial and temporal interpolation routine was developed to analyze tropopause variations from the enhanced western North Pacific radiosonde network used in TCM-90. These analyses were designed to explore the response of the tropical tropopause to the passage of a tropical cyclone, describing yet another component of the tropical cyclone-environment interaction. As the tropical cyclone approached, we saw evidence of the tropopause rising and warming, with sinking and cooling evident after the storm passage. There was limited evidence for sinking in the region of the eye, but the data resolution is inadequate to be unequivocal about this result. The spatial range of the tropopause response was surprisingly large – on the order of the tropical storm outflow extent.

A.5 TECHNICAL ACCOMPLISHMENTS:

To gain an understanding of the processes leading to tropical cyclone intensity change and the relationship of a tropical cyclone to its environment, we took a multifaceted approach, incorporating non-hydrostatic numerical modeling and observational analyses. Each of these approaches had its own set of challenges. Technical achievements designed to meet these challenges are described here.

(a) The Penn State/NCAR Non-Hydrostatic Mesoscale Model (MM5)

The Penn State/NCAR non-hydrostatic mesoscale model (MM5) is a valuable resource to the meteorological community. Its skill in simulating midlatitude weather events has been widely documented. It has evolved into a powerful forecast-oriented system, with advanced objective assimilation of real-time data. However, its roots are in an idealized, axisymmetric, hydrostatic model of tropical cyclones. It was our aim to return to this (tropical) application of the modern model by enhancing its current capabilities.

Our approach to the numerical investigation of tropical cyclone intensity change was to design a system of idealized simulations based on observational case studies and synoptic situations that have been hypothesized to be favorable for tropical cyclone intensification (e.g. Sadler 1976, 1978). To this end, we needed to add substantially to the current model suite. Our contributions are listed here:

(i) Design of a set of idealized, balanced, atmospheric structures that are physically representative of the real atmosphere, yet mathematically simple enough to enable easy alteration of various physical (amplitude, orientation, depth) and dynamical features (circulation, integrated potential vorticity, vertical wind shear).

(ii) Implementation of these structures as initial conditions to the present operationally-oriented model. Use of idealized initial conditions has rarely been attempted over the

last fifteen years and, due to the forecasting focus of the model developers, implementation of an option to do this had not been included into the priority list for future upgrades. We are working to change this and will maintain our own capabilities until this is so.

(iii) Coding and testing of a dynamical initialization system to balance the combined fields. Obviously, the sum of two balanced solutions to a nonlinear problem is not, itself, balanced. Hence, we still needed to adjust our model input to avoid non-physical evolution effects persisting throughout the simulation. To this end, a dynamic initialization system was implemented for the idealized initial conditions.

(iv) Modification of model boundary conditions for the idealized environment. Once again, the forecast focus of MM5 did not cater to our needs and we spent much time testing and implementing appropriate boundary conditions for the idealized simulations.

Each of these achievements represented a substantial contribution to MM5 using the talents of workers from this project (predominantly Ms Sytske Drury). We are grateful to the MM5 development team at Penn State, who ably assisted us with answers to questions and with helpful advice. Even still, this necessary work was accomplished on the watch of this project.

As with any numerical modeling project, additional time was required to test the various possible configurations of model parameterizations, determining which combination of physical treatments presented the most physically realistic results. This testing was also accomplished on the watch of this project.

We have taken advantage of all of the new options available to us after these substantial modifications and testing. We are now in the process of running, analyzing and documenting a meaningful sequence of simulations of a tropical cyclone-like vortex in a hierarchy of realistic environmental configurations. We believe this comprehensive survey will be of great use to both the tropical cyclone community and the wider community.

(b) Observational Analyses of Tropical Cyclones: Trough Interactions

(i) Software design and coding was completed for case studies of tropical storms in the presence of a midlatitude trough. One case of a tropical cyclone interaction with a TUTT (tropical upper tropospheric trough) was also included.

(ii) Advanced new graphical software was also developed to aid in presentation of this work.

(c) Observational Analyses of Tropical Cyclones: Broadscale

(i) An automated system for satellite data diagnostics of the tropical atmosphere was developed and tested.

(ii) This new technique was applied to data from an eighteen month period in the Atlantic Ocean.

(iii) Development of a smart spatial and temporal interpolation routine to analyze tropopause variations from western North Pacific radiosonde data. Analyses using data from the enhanced TCM-90 radiosonde network have been completed.

A.6 Reporting and Interactions:

Reporting of this work over the life of the grant has been extensive. This has included presentations to a wide variety of other audiences. A complete list of the written and oral reports of this work is included below.

Two seminars were presented at the Naval Research Laboratory (Monterey). These were incorporated into longer visits and discussions with personnel of both the NRL and the Naval Postgraduate School.

Three of the team members (Dr Evans, Ms Drury and Mr Guertin) have visited the Hurricane Research Division of AOML in Miami. Relaxed exchanges with the scientists there were very fruitful.

A.7 Relationship to Other Projects:

This project is related to the general objectives of ONR in its rôle to support fundamental research that has relevance to improvements in operational forecast products.

B. Statistical Information on Project

B.1 Publications Resulting From This Work:

Three journal articles, 10 conference papers and 2 Masters theses have already resulted from this work. These are listed below. Further journal articles are in preparation.

B.2 Journal Articles

Evans, J. L., and R. E. Shemo 1996 Automated identification and climatologies of various classes of convection in the Atlantic Ocean. *J. Appl. Meteor.,* **35,** 638-652.

Shemo, R. E., and J. L. Evans 1996 Contributions of various classes of convection to rainfall in the Atlantic Ocean. *Meteor. and Atmos. Phys.,* **60,** 191-205.

Evans, J. L., and K. S. McKinley 1997 Relative timing of tropical storm lifetime maximum intensity and track recurvature. *Meteor. and Atmos. Phys.,* (submitted).

B.3 Masters Theses

Shemo, R. E. 1994 Precipitation signatures of various classes of organized convection in the Atlantic Ocean. *Masters Thesis, Department of Meteorology,* The Pennsylvania State University, University Park, PA, August, 1994, 69pp.

Guertin, D. P. 1997 Potential vorticity diagnostics of tropical cyclones. *Masters Thesis, Department of Meteorology,* The Pennsylvania State University, University Park, PA, 107pp.

B.4 Conference Papers

Shemo, R. E., and J. L. Evans 1994 Precipitation signatures of various classes of organized convection in the Atlantic Ocean. Preprints of the *Seventh Conference on Satellite Meteorology and Oceanography,* 6 – 10 June, Monterey, CA, 334-335.

DAVIS, J. R. 1995 Further analyses of sea surface temperature effects on tropical cyclone intensity. Preprints of the *21st Hurricanes and Tropical Meteorology Conference,* 24-28 April 1995, Miami FL.

DRURY, S. 1995 The effects of vertical shear and vertical vorticity on the intensity of idealized tropical cyclones. Preprints of the *21th Hurricanes and Tropical Meteorology Conference,* 24-28 April 1995, Miami FL.

EVANS, J. L. 1995 Seasonal variation of organized tropical convection. Preprints of the *21st Hurricanes and Tropical Meteorology Conference,* 24-28 April 1995, Miami FL.

DRURY, S., AND J. L. EVANS 1996 Non-hydrostatic tropical cyclone intensification modeling using MM5. Preprints of the *11th Numerical Weather Prediction Conference,* 19-23 August 1996, Norfolk, VA.

GUERTIN, D. P. 1997 Potential vorticity diagnostics of hurricane Opal. , Proceedings of the 22nd **AMS Conference on Hurricanes and Tropical Meteorology,** 19-23 May, 1997, Fort Collins, CO.

DRURY, S. 1997 Modeling of tropical cyclone intensification as a result of interaction with midlatitude troughs. Proceedings of the 22nd *AMS Conference on Hurricanes and Tropical Meteorology,* 19-23 May, 1997, Fort Collins, CO.

EVANS, J. L., AND K. S. MCKINLEY 1997 Maximum Tropical Cyclone Intensity and Recurvature. Proceedings of the *22nd AMS Conference on Hurricanes and Tropical Meteorology,* 19-23 May 1997, Fort Collins, CO., 356-357.

EVANS, J. L. 1997 Tropical cyclone blobs: Intensity and motion changes. Proceedings of *The 1997 Joint Assemblies of the International Association of Meteorology and Atmospheric Physics and International Association for Physical Sciences of the Oceans,* pIM2-27, 1-9 July 1997, Melbourne, Australia.

B.5 GRADUATE STUDENT INFORMATION:

Graduate students involved in this work : **4**
Undergraduate students involved in this work : **1**
Graduate students supported on this grant : **3** [Ms Sytske Drury, Mr Dan Guertin (summer 1996, 1997), Mr Michael Pontrelli (summer 1996)]
Female graduate students supported on this grant : **1** [Ms Sytske Drury]
Ms Kathleen McKinley is an undergraduate student at Penn State, who became involved in the intensity/recurvature observational study I conducted in this last year. This work has resulted in her co-authorship on both a conference paper and journal article.

B.6 PRESENTATIONS BY PROJECT MEMBERS:

Seventeen presentations highlighting various aspects of this work were made through the course of the grant. Audiences ranged from tropical weather forecasters, to theoretical physicists, to members of the wider meteorological community including, of course, personnel at the Naval Research Laboratory (Monterey) and the Naval Postgraduate School. The complete list of talks is:

(1) **November 1993**: **Dr Jenni Evans** was an invited participant and speaker at the *World Meteorological Organization's Third International Workshop on Tropical Cyclones* in Hualtulco, Mexico

(2) **June 1994**: Poster presented by **Mr Robert Shemo** and **Dr Jenni Evans** at the *Seventh Conference on Satellite Meteorology and Oceanography* of the American Meteorological Society in Monterey, California, USA.

(3) **July 1994**: **Dr Jenni Evans** was an invited speaker at the second summer workshop (entitled "Diving Surprises") of the *Aspen Global Change Institute* in Aspen, Colorado.

(4) **November 1994**: **Dr Jenni Evans** was an invited participant and speaker at the *Florida State University Workshop on Satellite meteorology and NWP* in Tallahassee, Florida.

(5) **April 1995**: Talk presented by **Dr Jenni Evans** at the *21st Conference on Hurricanes and Tropical Meteorology* of the American Meteorological Society in Miami, Florida, USA.

(6) **April 1995**: Poster presented by **Ms Sytske Drury** at the *21st Conference on Hurricanes and Tropical Meteorology* of the American Meteorological Society in Miami, Florida, USA.

(7) **April 1995**: Poster presented by **Mr Joseph Davis** at the *21st Conference on Hurricanes and Tropical Meteorology* of the American Meteorological Society in Miami, Florida, USA.

(8) **June 1995**: **Dr Jenni Evans** presented a talk at the *American Geophysical Union Spring Meeting* in Baltimore, Maryland.

(9) **July 1995**: **Dr Jenni Evans** presented a seminar in the Department of Meteorology at the State University of New York (Albany), Albany, New York.

(10) **August 1995**: **Dr Jenni Evans** gave a presentation in the Center for Meteorology and Physical Oceanography at the Massachusetts Institute of Technology in Cambridge, Massachusetts.

(11) **April 1996**: Talk presented by **Dr Jenni Evans** in the Department of Earth, Atmosphere and Planetary Sciences, Harvard University, Cambridge, MA, USA.

(12) **June 1996**: **Dr Jenni Evans** presented a talk in the Department of Applied Mathematics and Theoretical Physics, Cambridge University, Cambridge, UK.

(13) **June 1996**: **Dr Jenni Evans** gave a presentation to members of the Climatic Research Institute, University of East Anglia, Norwich, UK.

(14) **July 1996**: **Dr Jenni Evans** presented a seminar at the Naval Research Laboratory, Monterey, CA, USA. This visit also encompassed meetings with a number of researchers at both NRL and NPS.

(15) **July 1996**: **Ms Sytske Drury** gave a presentation at the *MM5 Users Group Meeting*, Boulder, CO, USA.

(16) **August 1996**: **Ms Sytske Drury** gave a talk at the 11^{th} *Numerical Weather Prediction Conference*, Norfolk, VA, USA.

(17) **September 1996**: **Ms Sytske Drury** gave a seminar at the Hurricane Research Division, Miami, FL, USA.

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